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# MEASUREMENTS WITH THE ELI-NP CAVITY BEAM POSITION MONITOR READ-OUT ELECTRONICS AT FLASH

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*Abstract*

The Extreme Light Infrastructure - Nuclear Physics Gamma Beam System (ELI-NP GBS) will be installed and commissioned starting within the next year in Magurele, Romania. It will generate gamma beam through Compton back-scattering of a recirculated laser and a multi-bunch electron beam, produced by a 720 MeV LINAC. In order to obtain bunch by bunch position measurements, four cavity beam position monitors (cBPM) near the two interaction points are foreseen. Extensive tests on the cBPM read-out electronics, recently developed by Instrumentation Technologies and acquired for ELI-NP GBS, were performed in laboratory at INFN-LNF and at FLASH in DESY, during the user operation. In the latter case, three cBPMs installed along the LINAC, with similar features as the ones of ELI-NP GBS, were used as measuring devices and signal sources for the read-out electronics under test. We present here the measurements collected and the related analysis, with a particular focus on the beam position measurement resolution.

## INTRODUCTION

The ELI-NP GBS (Extreme Light Infrastructure-Nuclear Physics Gamma Beam System) is currently under construction at IFIN-HH in Magurele (Romania) [1, 2]. It is a high intensity and monochromatic gamma source, based on Compton back-scattering at the interaction between a high quality electron beam and a high power recirculated laser. The electron beam will have a repetition rate of 100 Hz and it will be composed by pulses of a maximum of 32 bunches, with a bunch-spacing of 16.1 ns and a bunch charge in the range of 25-250 pC.

A total of four cavity Beam Position Monitors (cBPMs) will be installed immediately before and after the two laser-electrons interaction points (at 280MeV and 720 MeV). The goal is to guarantee a position measurement for every bunch with a resolution of 1 μm in the range of ±1 mm. The cBPMs are the PSI BPM16 model [3], consisting of one “reference” resonator for charge measurements (by measuring the amplitude of the monopole mode $TM_{010}$) and one “position” resonator for transverse position measurements (by measuring the amplitude of the dipole mode $TM_{110}$), both with a resonance frequency of 3.284 GHz and Q = 40. The low value of Q assures that the signal produced by one bunch will decay fast enough to not interfere with the signal coming from the next bunch [4].

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## THE READ-OUT ELECTRONICS

The read-out electronics for ELI-NP GBS are the “Libera CavityBPM”, developed by Instrumentation Technologies and already presented in [5, 6].

Each module is capable to acquire the signals produced by the “position” resonator (“X”, “Y”) and by the reference resonator (“I”) of one cBPM. At the front-end stage, the signals are filtered from unwanted frequency component and their amplitudes are adjusted by means of variable attenuators (0 dB/ 32 dB), depending on the beam conditions (e.g. charge, position). The signals are then down converted to an intermediate frequency, filtered and digitized. The local oscillator frequency and the ADC sampling rate (500MS/s, 14 bit) are generated by two PLLs, locked on an external signal reference, which, in the case of ELI-NP GBS, will have a frequency of 62.087 MHz. The digitized signals are processed by a 100-bin FIR filter, called “Deconvolution filter”, which is used to extract the individual bunch signals from the stream of data and to limit the superposition between signals of consecutive bunches. After the digital processing, the absolute transverse position ($x_b$, $y_b$) of each bunch is obtained with the equations:

$$x_b = K_x \frac{V_x}{V_i} \quad y_b = K_y \frac{V_y}{V_i}$$

where $V_x$, $V_y$, $V_i$ are the amplitudes associated to each signal (“X”, “Y”, “I”), computed through a sum of squares formula on the digital data and $K_x$, $K_y$ are calibration constants, which take into accounts the sensitivity of the resonators, the attenuation used and, if necessary, the attenuation of the cables.

In order to determine the sign of the transverse beam position, an I/Q demodulation of the signals is performed to measure and compare the phase of the position resonator signals (“X”, “Y”) with the phase of the reference resonator signal (“I”).

## TEST-STAND AT FLASH1

The validation and the first measurements on the recently developed “Libera CavityBPM” were performed in laboratory at INFN-LNF [6]. Although all the functionalities were validated and the tests on the measuring performance of the “Libera CavityBPM” were promising, it was not possible to fully test the resolution, because we were limited by the noise introduced by the signal generator used.

Thus, we performed a second session of tests at DESY, by using a cBPM test stand at FLASH1 [7], shown in

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Figure 1. The three cBPMs (EU-XFEL undulator type) installed on the test stand, which are similar in design to the ELI-NP GBS ones (see Table 1), could be moved in both transverse directions with remote movers.

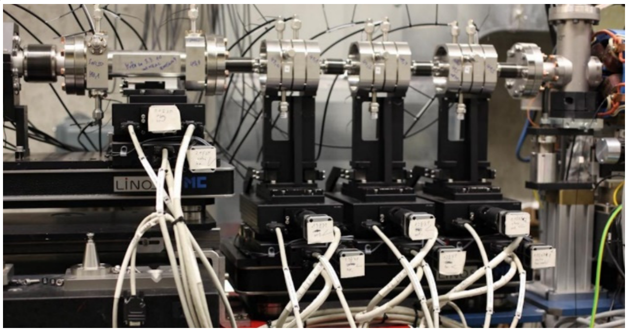

Figure 1: CBPM test-stand at FLASH1 with three undulator cBPMs (on the right) on remote movers [7].

We connected the cBPMs to three "Libera CavityBPM". The PLLs were adjusted in order to accept the reference signal provided ($f_{ref}$=216.7 MHz) and to produce appropriate frequency for the Local oscillator (3675.3 MHz) and for the ADC (497.53 MHz).

Table 1: Nominal Parameters of ELI-NP GBS and EU-XFEL Undulator Type cBPM

| cBPM Parameter | ELI-NP | EU-XFEL |
|---|---|---|
| $Q_L$ | 40 | 70 |
| $TM_{110}$ frequency ("position resonator") [GHz] | 3.284 | 3.3 |
| $TM_{010}$ frequency ("reference" resonator) [GHz] | 3.284 | 3.3 |
| "Position" resonator sensitivity [V/mm/nC] | 7.07 | 2.84 |
| "Reference" resonator sensitivity [V/nC] | 135 | 60 |

The beam-train provided at FLASH1 during the three days of measurements had a repetition rate of 10 Hz with a time interval between the bunches of 1 µs or higher. Since the time interval between bunches was much higher than 16.1 ns, we considered all the measurements taken as in single-bunch mode. We took the data for bunch charges of 200 pC and 500 pC.

## MEASUREMENTS

### *Output Signal and Deconvolution Filter*

The typical sampled signal at the passage of a single bunch is showed in the upper plot of Figure 2. The plot is relative to channel "X", with a bunch off-centered on the horizontal plane. Similar signals are captured at channels "Y" and "I". The signal length covers approximately 20 samples (~40 ns). By applying the digital deconvolution filter, the signal is compressed into 8 samples (lower plot of Figure 2), in order to perform multi-bunch measurements for the ELI-NP GBS applications. From the measurements performed at DESY in single-bunch mode, the effects of the deconvolution filter are negligible in terms of accuracy and precision.

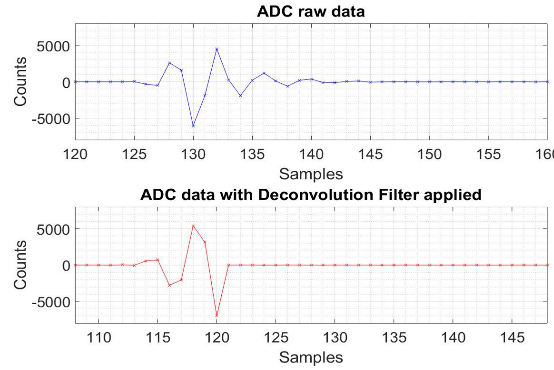


Figure 2: Comparison between ADC output without Deconvolution filter (upper plot) and with Deconvolution Filter (lower plot) of channel "X" at the passage of an off-centered bunch.

### *Resolution*

cBPM resolution was determined by measuring the residual, that is the difference between the position of the beam as measured by the cBPM in question and the predicted position as calculated from the beam's position in the two other cBPMs. We used the central cBPM as the device under test (cBPM2) and the external ones (cBPM1, cBPM3) to calculate the predicted position [8-10]. By considering the distance between the cBPMs equal (which is a good approximation of the real case) the residual on the horizontal plane ($ResX_2$) is calculated as:

$$ResX_2 = X_2 - \frac{X_1 + X_3}{2}$$

where $X_1$, $X_2$, $X_3$ are the horizontal positions of the bunch measured respectively by cBPM1, cBPM2, cBPM3. Same applies for the vertical plane.

The standard deviation of the residual is then given by:

$$\sigma_{ResX_2} = \sqrt{\sigma_{X2}{}^2 + \frac{\sigma_{X1}{}^2 + \sigma_{X3}{}^2}{4}} = \sqrt{\frac{3}{2}} * \sigma_X$$

where we assumed that the cBPMs have the same resolution ($\sigma_{X1,X2,X3} = \sigma_X$). By reversing the equation, the resolution $\sigma_X$ of the cBPM under test is obtained.

We measured the residual and its standard deviation and calculated the resolution of cBPM2 for different horizontal position of the beam in respect to the electromagnetic center of the cBPMs, by moving the latters with remote movers on the horizontal plane.

From the position calculated by the three cBPMs at different horizontal positions (Figure 3), it is possible to observe that the sensitivities are not the same for the cBPMs, especially for cBPM1 (9% higher than cBPM2). This difference, calculated by means of linear regression, could derive from mechanical differences or different cable attenuations between the cBPMs and it was compensated after the data have been taken. From the data collected, we also measured (with each cBPMs) a beam fluctuation of 18 µm (std).

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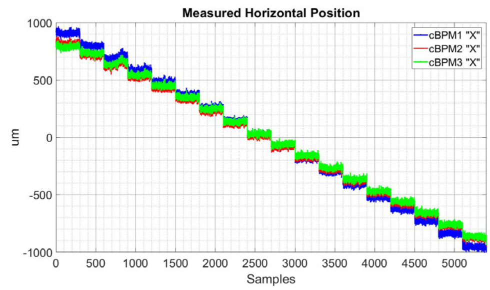


Figure 3: Measured horizontal position of the three cBPMs, obtained by moving them with steps of 100 µm in the horizontal plane (bunch charge = 200 pC).

Resolution measurements performed for different bunch charges, with a maximum range of measurements set at ±1300 µm (by means of the variable attenuators) are shown in Figure 4.

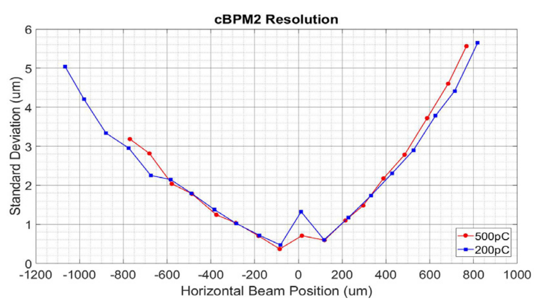


Figure 4: cBPM2 horizontal position measurement resolution for different bunch charges and different beam positions. Maximum range of measurements: ±1300 µm.

The resolution is dependent on the beam position (i.e. the amplitude of the cBPM output signal) and get worse for a beam farther from the electromagnetic center of the cBPM. This behaviour could be explained with the presence of phase noise. For sine-like signals, phase noise is proportional to the amplitude of the involved signals and could explain the resolution trend shown in Figure 4. Contribution to phase noise could come from the external reference signal, the PLLs used to down-convert the input signal and from A/D converters. Laboratory measurements performed by Instrumentation Technologies showed negligible amount of phase noise from the internal components of the instruments. Thus, the main source of it could be the jitter of the reference signal used ($f_{ref}$=216.7 MHz), whose measured value is 3.2 ps. This amount of jitter is in first approximation in agreement with the resolution calculated, even though a full analysis of its impact has to be completed, by taking into considerations the behaviour of the PLLs and the fact that the position is calculated as the ratio between two channels (for example, "X" and "I"), both affected by the same source of phase noise.

Phase noise could also explain the resolution measurements obtained by using different maximum range of measures (by setting the variable attenuators of the read-out electronics). In principle, by using a smaller range of measurement, the signals are stronger (they are less attenuated at the input stage) and the resolution should improve accordingly. This was verified to be not true: if one does not consider the central point of the plot in Figure 5 (explained later in this paragraph), it is possible to see that the resolution is roughly the same in the two cases. This would be in agreement with phase noise, which would be higher for stronger signals, neglecting the resolution improvement by choosing a smaller measurable range.

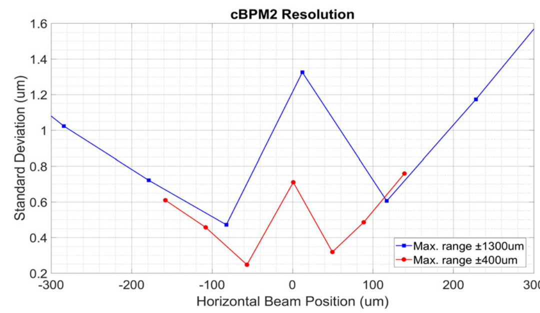


Figure 5: cBPM2 horizontal position measurement resolution for different maximum measurable ranges. Charge of the bunches = 200 pC.

The second effect to notice from the resolution measurements is the worsening of the resolution with a beam at the center. This behaviour comes from the fact that the cBPM signal strength with a centered beam is very low (ideally "zero") and the digitized signal is dominated by noise and offset. In such condition, the algorithm used to calculate the phase of the input signals (to determine the sign of the transverse beam position), does not operate properly and produces erratic measures of the signal phase, leading to an overall worsening of the resolution. This effect is present in a range of ±3 µm from the electromagnetic center of the cBPM.

## CONCLUSION

Cavity Beam Position Monitors will be installed at ELI-NP GBS, to perform high resolution bunch by bunch measurements at the two interaction points. Tests at FLASH1 in DESY were performed on the read-out electronics, recently developed by Instrumentation Technologies, by using a test-stand with cBPMs, similar in design to the ones for ELI-NP GBS.

The measurements show that the resolution is dependent on the transverse beam position (worse for off-centered beam). One possible reason could be the presence of phase noise, introduced by the reference signal used. This has to be confirmed with further measurements. Nevertheless, the resolution achieved is on good levels, being under 1 µm in a beam position interval of ±250 µm within the electromagnetic center of the cBPM and with a maximum range of measures of ±1300 µm. Moreover, by using a more stable reference signal in ELI-NP GBS, the resolution should improve accordingly. Other functionalities and parameters of the read-out electronics, already tested at LNF-INFN, are confirmed to work properly and within acceptable levels.

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